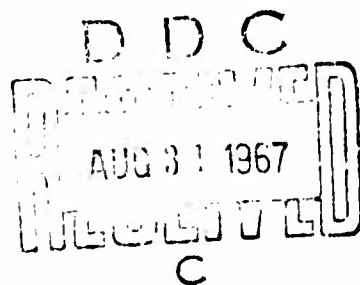# THE THEORY AND AN EXPERIMENT
ON A SIMPLE FUNGUS-EATER GAME

by

M. TODA AND H. MIYAMAE

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WESTERN MANAGEMENT SCIENCE INSTITUTE

University of California, Los Angeles

University of California

Los Angeles

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"THE THEORY AND AN EXPERIMENT ON A SIMPLE FUNGUS-EATER GAME"

Masanao Toda and Hiroko Miyamae

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ABSTRACT

The purpose of the fungus-eater approach is to obtain the optimal
decision rules that handle means-end relations prescribed by a dynamic
programming type situation to produce the maximum expected end-value. An
experiment recently done at Hokkaido University is analyzed, and the behavior
of human subjects is compared with the optimal behavior of the fungus-eater.
Under the situations employed in the experiment, the fungus-eater model
seems to work well for predicting the human S_s^1 behavior.

THE THEORY AND AN EXPERIMENT ON A SIMPLE FUNGUS-EATER GAME [1]

Masanao Toda and Hiroko Miyamae [2]

1. A Brief Biography of the Fungus-Eater

In order to discuss the fungus-eater approach, we should first introduce the fungus-eater to those who are not acquainted with him as yet. The fungus-eater is a hypothetical robot living in the 21st Century. He is a uranium miner, and the only one, on the planet called Taros. Taros is in no stellar chart, since it has not yet been discovered. The fungus-eater is a robot of a single-track mind, as any decent robot is supposed to be. The fungus-eater happens to be a uranium-bug. The sole purpose of his life is to collect uranium ore which is distributed over the surface of Taros. His craving for more uranium is never satiated.

Even a robot has a physiological need. The fungus-eater needs energy supplies in order to move around Taros to collect uranium ore. So he eats wild fungi growing at random on the ground of Taros, and his stomach, a biochemical energy converter, extracts the necessary energy. Besides a mouth to eat fungi, he also has a pair of eyes to detect fungi and uranium. He also has a brain-computer so that he can plan.

This is the overview provided to experimental Ss to familiarize them with the abstract structure of the fungus-eater games.

2. The Purpose: A Deductive Approach

The major purpose of the fungus-eater approach is to study how people plan, or how people, individually and collectively, organize their behavior

over time. Anyone who manages to keep himself as a free member of a society must have organized his behavior in a certain specific way. Otherwise, he would sooner or later be detected, labeled as a social or a mental aberrant, and sent to an institution specially built for his type of aberrants. Note that the behavior of the clients of these institutions is not necessarily unorganized. In most cases, their behaviors are organized, but in some aberrant fashion. What is then "normal" behavior? We can tabulate a very long list of normality criteria picked up from legal and psychiatric sources, but still, very little is known about the principle of normality. There is, however, one clue: Normal human behavior must be adaptive to man's environment; otherwise, we cannot survive.

What would be a good research strategy in studying something as complicated as the organization of human behavior? The traditional research philosophy in experimental psychology may be characterized as "primarily inductive." There is, of course, no science which is entirely inductive or entirely deductive. An experimental psychologist will use a theory, a hypothesis, or any deductive mechanism of the sort, at least when he wants to decide what experiment he should conduct next. There are, however, not many theories in experimental psychology which have really strong deductive power, and there seems to be a popular attitude among some experimental psychologists to consider theories as a necessary evil, if they are necessary at all. Such an attitude is quite understandable with regard to the enormous complexity of human behavior before which any strongly deductive system is almost bound to fail as a descriptive theory.

However, it is also true that without the aid of a really powerful

deductive system we can only scratch the surface, and can never penetrate deeply into the heart of the complexity. The only way to resolve this dilemma seems to be to develop deductive systems as deductive systems, which are not, for the time being, prediction-oriented--just like pure mathematics. What we really want to possess is a branch of mathematics which is specially tailored to effective theory building in the behavioral science. How can such a branch of mathematics be started? We have a very useful clue here that human behavior is adaptive to the environment, individually and collectively. Adaptation is not a well defined concept, and we need a precise redefinition. However, if we could replace the notion of adaptive behavior by a closely related notion of optimal behavior, such a branch of mathematics already exists as the normative decision theory, including Bayesian statistics and dynamic programming. Take Bayesian statistics, for example. Bayesian statistics is not a descriptive, predictive theory, and whether or not people are really Bayesian is extrinsic to the value of Bayesian statistics. But if people are really Bayesian, or close ot it, then undoubtedly Bayesian statistics will supply us a good prefabricated framework for a descriptive, predictive theory. And this is exactly what the fungus-eater approach aims at.

The fungus-eater approach is very close to dynamic programming in mathematical problems dealt with. The difference lies, however, in the respective goals. Dynamic programming is primarily oriented to its normative merit. Whether or not the fungus-eater approach will acquire a normative merit is of little concern to us. Indeed, who cares for the efficiency of a hypothetical robot on a hypothetical planet? Our primary concern is to investigate the logic of environment-organism interaction as reflected in the structure of the optimal

behavior. So we shall start with a very simple environment and a very simple organism (or a robot) both abstractly defined, and then solve for optimal behavior of the robot in the environment. If this is done, we shall then further develop both the environment and the organism so that they will gradually approach man's environment and man himself.

Of course we will never be able to put all the ingredients that make up man and his environment into a theoretical system. Any information processing system will explode with such a heavy load. So we have to restrict our attention to essential ingredients. But who knows the essential elements of man and his environment? Knowing them is in fact our ultimate goal. So here we need to rely on a negative feedback technique, and our deductive approach calls for inductive intermissions, just as the inductive approach of experimental psychologist requires deductive stages of planning between experiments. So we run experiments to guide our course. If the optimal behavior of the fungus-eater is getting closer to the human Ss' behavior playing the corresponding "fungus-eater games," then we can be more confident that we are one the right track.

So much for the philosophy. Now let us return to the story of the fungus-eater.

3. The Common Background of Simple Fungus-Eater Games

For the time being the fungus-eater is the only creature in the world of Taros without any companion fungus-eaters or enemy fungus-eater eaters. Suppose that he has a finite life-span, 10 Taros years, say. Let T be the total amount of uranium he may collect during his lifetime. Then the fungus-

eater's goal is expressed as: Maximize T. The ten year life-span of the
fungus-eater does not mean that he can live up to ten years for sure. The
fungus-eater can make his uranium-hunting trip only as long as he has a fungus
supply in his stomach to keep him going. So, if he happens to run out of
fungus, he cannot move, and we may as well define this as the death of the
fungus-eater by starvation.

Will he be afraid of death? The fungus-eater has no feeling. Even if
he has, survival _per se_ is no part of his single track goal. He would die
early without regret if it is an unavoidable consequence of maximizing the
total uranium return in his lifetime. However, such a situation may be rare.
More often than not, the situation will dictate keeping himself alive as long
as possible so that he can collect more uranium. His survival depends solely
upon the fungus supply in his stomach, so sometimes he may appear as if he is
survival-oriented and is an avaricious eater of fungus. But if he behaves
that way it is only because that is a good strategy to obtain more uranium.

We particularly emphasize this point because it is important to distinguish
two kinds of values, the _means value_ and the _end value_, the distinction being
rather neglected in traditional decision theory. This is why we considered
fungus and uranium as the only entities in the fungus-eater's world. It is
the simplest case for studying the means-end relationship.

We need, however, a few more elements to make the situation concrete. In
order for the fungus-eater to organize his behavior in a meaningful way, he
has to have some information feed-back from the environment. So let us give
him a sense organ. For simplicity, let us assume that he can detect every
object in a circular area around him with a fixed radius, which we shall call

his visual span.

From here on there are two opposite approaches. One is to simplify the problem by adding further environmental constraints so that we have access to analytical solutions, and then gradually remove these non-essential constraints while sharpening up our mathematical tools. The results will be exact but the process will be slow. On the other hand, we may temporarily give up obtaining rigorous mathematical solutions, satisfying ourselves only with qualitative results, and then jump directly to more interesting cases. For example, we may discuss such cases as follows: Suppose that the fungus-eater is no longer alone. There are fellow fungus-eaters. Does it do any good to cooperate? If it does, under what circumstances? If they exchange fungus for uranium, what would be the fair price? Do they make contract agreements between them? If they do, what would be the punishment for breaking a contract? And so on. Of course, these two lines of approach can be undertaken simultaneously, and some study on the second line is now under way. However, we have been concentrating upon the first line in the past few years, and what will be discussed here is a part of the outgrowth of this effort.

The simplest case we considered is as follows: The fungus-eater can move only along a simple chain-type path structure as illustrated in Fig. 1. He can move only to the right in this figure.
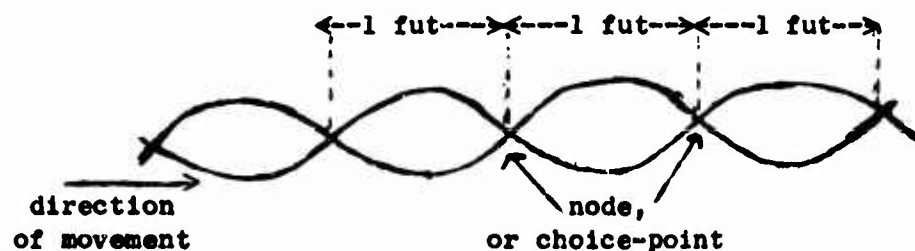

FIG. 1. The path-structure in simple fungus-eater games

So the only choice he should make is whether to take the north-bound path
or the south-bound path at each intersection or node. The distance between
adjacent nodes is constant. We shall call the amount of fungus to be consumed
for the fungus-eater to cover this distance one _fut_ (fungus unit), and call
this distance, too, one fut distance. The radius of the fungus-eater's visual
span is also assumed to be one fut.

The fungus-eater's choice of path depends on objects he detects within his
visual span. The objects are fungi and uranium ores. The uranium ores are
all of the same size and of the same value. Fungi, too, are all of the same
size, and each fungus has $\underline{a}$ futs nourishment, where $\underline{a}$ is a fixed parameter.
Fungi and uranium are never located at a node, and each path contains no more
than one object; one uranium, or one fungus, or nothing. So the only non-
trivial decision situation the fungus-eater may face is when one path contains
a uranium ore and the other a fungus. The fungus-eater has an infinite stomach
(fungus-storage) capacity. This is the background common to the four cases
we consider below.

4. The Solutions of Simple Fungus-Eater Games

We have solved the optimal behavior of the fungus-eater for the following
four cases: 1) the infinite, coexistence case, 2) the infinite, independence
case, 3) the finite, coexistence case and 4) the finite, independence case.
In the infinite cases the life span of the fungus-eater is infinite so that he
can die only by starvation. In the finite cases the fungus-eater has a finite,
fixed life span. In other words, he can travel at most a certain, n_o futs,
distance, even if he managed to survive to complete the whole trip, he must die

then and there. The fungus-eater knows when this doomsday will come. In the
coexistence cases a fungus and a uranium ore appear simultaneously when they
do appear, one on the northbound path and the other on the southbound path.
The probability p of their joint appearance in each node-to-node area is
constant and independent of past occurrences and is known to the fungus-eater.
In the independence cases, the restriction of joint appearance is removed.
They may appear together or separately, but the two paths can never contain
more than one object. Thus, in the independence cases there are two constant
probabilities, one for the appearance of fungus and one for uranium, which
are mutually independent. We have obtained anlaytical solutions for the first
three cases, but only numerical solutions for the last case.

Remember that in all four cases the only non-trivial decision the fungus-
eater should make is which path to choose when he sees both a fungus and a
uranium ore. Which should he choose? In Case 2 (infinite, independence)
and Case 4 (finite, independence) a fungus or a uranium may appear alone.
In that situation he could never be worse off by taking whatever appeared.
When there is nothing, there is no difference whichever path he takes. So
from now on we shall only refer to the decision rule for the non-trivial choice.

In Case 1, the infinite, coexistence case, the solution is very simple:
Always choose uranium if the product of the two parameters, p, the probability
of the joint appearance of uranium and fungus, and a, the energy content (in
futs) of a single fungus, is less than one. Let x_o be the fungus-eater's
original fungus supply in fut units. Then his life under this decision rule
is exactly the time he needs to cover x_o futs distance. Such is a short life
for an immortal fungus-eater. But he makes no progress on his true goal by

eating fungi and extending his life. If, on the other hand, the product pa
is greater than one, the optimal decision rule is to choose fungus all the
time. One may naturally wonder, if the fungus-eater is choosing fungus all
the time, how he gets any uranium under the coexistence condition. But don't
worry--this fungus-eater is immortal. He will first collect an infinite amount
of fungus and then will set forth to collect an infinite amount of uranium.
Such is, of course, a mathematical fiction. But the nature of the solution
will be intuitively clear. [3]

The solution for Case 2, the infinite, independence case, is slightly
more complicated since it involves three parameters. The solution is given
in [Toda, 1963], and will not be discussed here. The solution for Case 3 is
similar to that for Case 1. When the product, pa, is less than one, choose
uranium all the time. When it is greater than one, take fungus. Unlike
Case 1, however, it is both impossible and unnecessary for the fungus-eater
to collect an infinite amount of fungus when he is mortal. He only needs to
collect enough to keep him going until doomsday--or one fungus less, depending
upon the relationship between n_o, the life span, and x_o, the initial fungus
supply (a point we shall not elaborate here). Then he switches to solely
collecting uranium and keeps this up until doomsday.

So far, the solutions have been rather trivial, in the sense that each
solution has only two values, depending only on the sign of pa-1. A non-trivial
solution is obtained only in the last of the four cases, the finite, inde-
pendence case. For the purpose of illustrating the solution of Case 4, it is
convenient to use the internal decision context diagram (abbreviated as
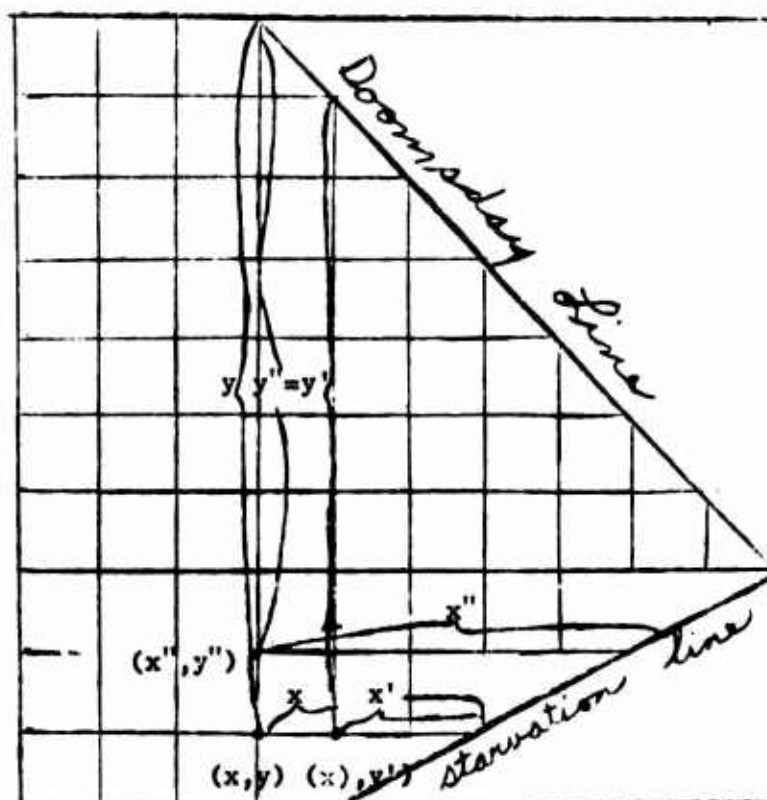IC-diagram) given in Fig. 2.

FIG. 2. IC-diagram for the Fungus-eater
in Case 3 and Case 4 (a = 3)

The only variables upon which the fungus-eater's decision should depend are the fungus supply in his stomach, x, and his remaining life span, y. The pair (x,y) is called the internal decision context of the fungus-eater at each given moment. Each possible internal decision context (x,y) is represented by a node in the IC-diagram in such a way that the horizontal distance between a point and the oblique line called Starvation Line gives the x coordinate of the point, and the vertical distance between the point and the other oblique line called Doomsday Line gives its y coordinate. Remember that the value of y must be reduced by one as the fungus-eater moves one fut distance. Now in Fig. 2 take a look at the y-coordinates of the point immediately on the right of (x,y), (x',y'), and of the point immediately above the same point, (x",y"). Obviously y'=y"=y-1. So these two points satisfy the above requirement for the fungus-eater's internal decision context after he made a one-fut trip from (x,y). The value of x must also be reduced by one after a unit trip if the fungus-eater did not eat a fungus during the trip, and this condition is met by the point, (x',y'). If the fungus-eater ate a fungus during the unit trip, x is increased by a-1. In Fig. 2 the value of a is chosen as 3. So this condition is met by the point, (x",y"). To summarize, the point in the IC-diagram representing the fungus-eater's internal decision context always moves by one step after each unit trip, to the right if he did not eat a fungus and upward if he ate a fungus. From the above argument, it will also be clear that Doomsday Line always has a slope -1, and Starvation Line has a slope $\frac{1}{a-1}$.

Note that the solutions of our fungus-eater games can conveniently be represented as partitions of the corresponding IC-diagrams, since the solution

is the optimal decision rule wnicn assigns either one of the two values U (cnoose uranium) and F (choose fungus) to every possible internal decision context. So, for example, an optimal solution in Case 3 when a = 3 ana pa > 1 is given by horizontally dividing the IC-diagram into two regions, the U-region and the F-region, as shown in Fig. 3. The optimal decision is U or F according to wnetner the internal decision context is in the U-region or in the F-region, respectively.
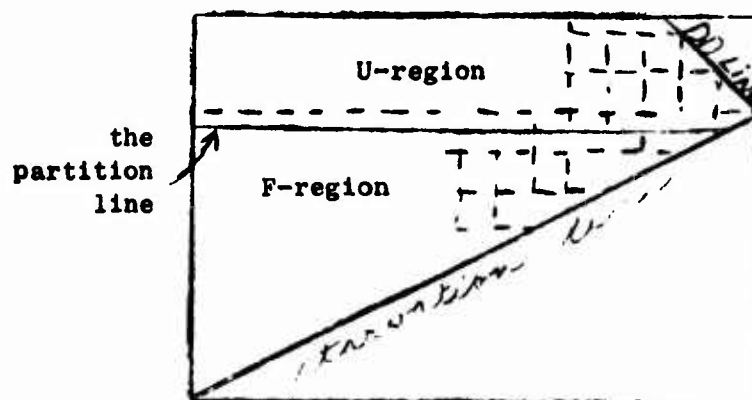

FIG. 3.   The optimal partition of
IC-diagram in Case 3

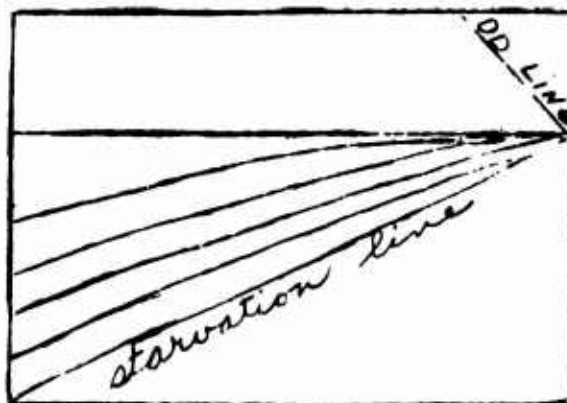Likewise, Fig. 4 shows some examples of Case 4 solutions.   For each line, the

FIG. 4.   Illustrative examples of the critical
fungus-supply level curves in Case 4.
For exact curves and the values of
parameters, see [Nakahara & Toda, 1964].

region above the line is the U-region and the region below the line is the F-region. Let us call this line the critical fungus supply level curve (or function), since whenever the fungus-eater's supply falls below this level he should get fungus.

Since the critical fungus level curve in Case 4 is sensitive to the densities of fungi and uranium ores, we decided to run an experiment to see how good college students were in comparison to the fungus-eater in this fungus-eater's environment. First we built an apparatus to display the IC-diagram directly to Ss. Various colored lamps were flushed on and off to indicate the location of each S's internal state, the existence of a fungus and/or uranium and so on. We are not, however, very happy with the result we obtained. (The result is given in [Miyamae, 1965].) Most of the Ss behaved according to a fairly clearcut decision rule from which we could easily infer the critical fungus level curve for each S under each condition. The curve, however, was a straight line in most cases. A straight line can be a fairly good approximation of the optimal critical fungus level curve like those shown in Fig. 4, particularly when the S's initial fungus storage is not very large, if the straight line is properly drawn. But the fact is that the straight lines Ss produced are, in most cases, those which connect their starting points in the IC-diagram and the origin (where Starvation Line and Doomsday Line cross), and they are not sensitive to the change in probabilities at all.

Whether or not this result is reliable is still open to question, particularly because there is a possibility that the Ss' attention might have been too much distracted by the huge colorful display apparatus, which, furthermore, occasionally misbehaved. This experiment, therefore, must be rerun to see if

we can reproduce the same result without using this apparatus. However, we decided to do experiments with other simpler cases first so that we can give a proper interpretation to whatever result we might obtain by rerunning the Case 4 experiment. Miyamae recently conducted an experiment with Case 1, the analysis of the data is still under way, and the following is a preliminary report on the analyses made so far.

5. Experiment

The experimental conditions are given in Table 1. The Ss were students at Hokkaido University who were taking the introductory psychology course. The course is normally offered to freshmen students, who belong to either of the following four departments: Premedical, Natural Sciences, Cultural Sciences and Fishery.

Experimental Conditions: Table of p Values

Groups	Ss	Session 1	2	3	4
G1	87	.5	.5		
G2	24	.3	.3	.3	.5
G3	86	.35	.35	.5	.5

TABLE 1

Our Group 1 Ss consist of the students from the premedical and natural sciences class, Group 2 from the fishery class, and Group 3 from the cultural sciences class. So our three groups are not homogeneous in intelligence and disposition. We were glad, therefore, when we found that they behaved in a fairly similar way in comparable conditions. The Ss in each group were run together. The value of probability p (the probability of the joint appearance of fungus and uranium) for each group for each session is listed in Table 1. The value of a (the energy content of a fungus) is fixed at 3 under every condition. Note that the value of the product pa is less than one for p = .3, and greater than one for p = .35 and = .5. So in the former case the optimal strategy is to choose uranium all the time. In the latter case the optimal strategy is, officially, first to choose fungus infinitely many times. This strategy, however, works only if the experiment continues infinitely long. Although the experimenter did her best by not telling the Ss when the experiment would be over, the Ss must certainly have known that the experiment would sooner or later be terminated. So there was an element of ambiguity in the situation, and it is one of the points of interest to know how Ss would interpret this ambiguity. All the Ss started with 15 futs of initial fungus supply. The whole situation was presented to them as a game, and they were asked to compete with each other. The rules were fully explained, and the value of the proba- bility p was told at each session.

On each trial each S made a predecision before knowing whether or not a fungus-uranium pair would be present on that trial. Then, after all the Ss made their predecision, E told them the presence or non-presence of a pair. If it was not present, their fungus storage was reduced by one fut independent

of the predecision made, and they proceeded to the next trial. If a pair was present, each S was committed to his predecision for the choice between uranium and fungus. The Ss who took fungus increased their fungus storage by two. Those who chose uranium added one unit to their uranium collection.

The predecisions as a function of the fungus supply constitute the data we discuss here. Fig. 5 gives the results. Each curve gives the percentage of fungus-choice over uranium plotted against the fungus supply under each condition. First, let us pay attention to the top three sets of curves.

They are the results obtained with $p = 0.5$. All the curves agree with each other in their general shape; the frequency of fungus-choice drops as the fungus storage increases, but the way it decreases is not homogeneous. A sharp drop is observed at around 5 futs of fungus supply. The effect is conspicuous enough to lead us to suspect that quite a few Ss might have set up a fairly stable critical fungus supply level at around that value and behaved accordingly, i.e., one switches from U-choice to F-choice when his fungus supply level fell below the critical level, and vice versa.

Before discussing this point further, let us take a look at the other curves, too. The two curves at the bottom right are obtained with $p=0.35$. The value of pa is still over one, but just slightly. Note that the Session 1 curve does not show any sharp drop effect, but the Session 2 curve shows it clearly. This, combined with the observation that Group 1 (for $p=0.5$) shows an overall decrease of fungus-choice ratio from Session 1 to Session 2, seems to indicate that there is some learning of whatever to be learned in early sessions. The very close agreement between Session 3 curve and Session 4 curve for Group 3 may suggest that the learning does not require too many sessions.
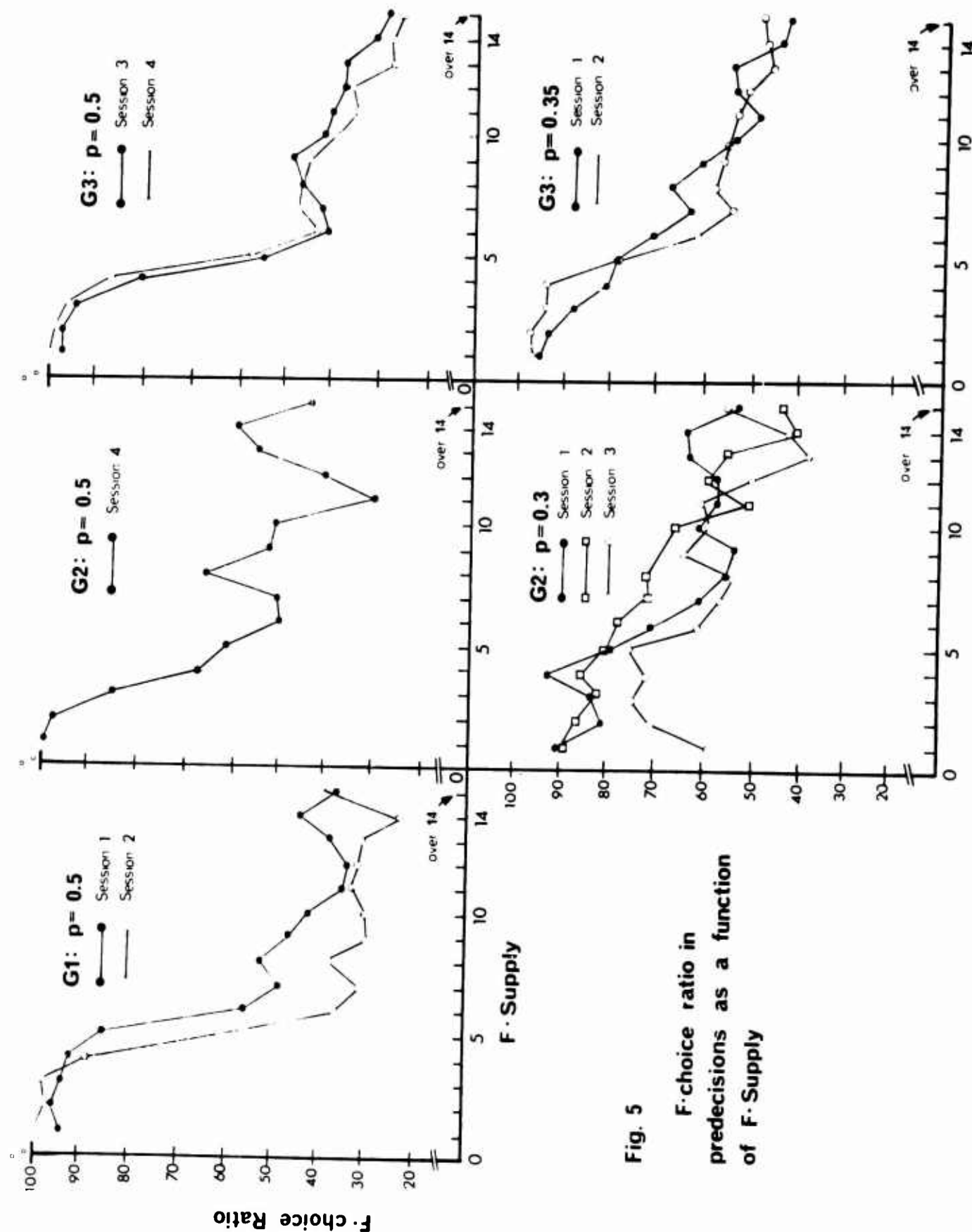
Fig. 5

F·choice ratio in
predecisions as a function
of F·Supply

Now let us turn to the Group 2 curves for p=0.3. Note that for these
three curves the value of pa is 0.9, below 1; so the optimal strategy is to
only collect uranium and to pay no attention to fungus at all. It would be
hard to imagine anything so remote from optimality as the behavior of Group 2
Ss shown here. But we cannot blame them for their foolishness. This optimal
strategy means a very short "playing" life, and it must be kind of boring to
finish early and watch other Ss keep playing. Besides, note that the difference
between their probability, 0.3, and the probability used for the first two
sessions for Group 3, 0.35, is only 0.05, and the optimal strategy with the
latter probability positively encourages choosing fungus. As a matter of fact,
the Session 1 and Session 2 curves of Group 2 are fairly similar to Session 1
curve of Group 3. One significant fact here, however, is that the Group 2 Ss
with probability 0.3 failed to exhibit the sharp drop effect, which the same
Ss immediately did as the probability is changed to 0.5 in Session 4. [4]

For the purpose of knowing the reason that caused a sharp drop effect, we
analyzed the sequences of predecisions of Group 3 Ss individually. (Similar
data analyses for the other two groups are now under way.) As expected, the
first thing we discovered is that there are many Ss who apparently established
clear-cut, stationary critical fungus-storage levels. The term "stationary"
is used here in a rather broad sense that the critical fungus supply level
either stays constant or changes smoothly and monotonically. As a matter of
fact, we could identify six dominant types of stationary critical fungus-
storage curves, as illustrated in Fig. 6. Note that in every stationary type
found in the data the critical supply level never increases with time. (In
other words, the distance between the critical level curve and Starvation Line
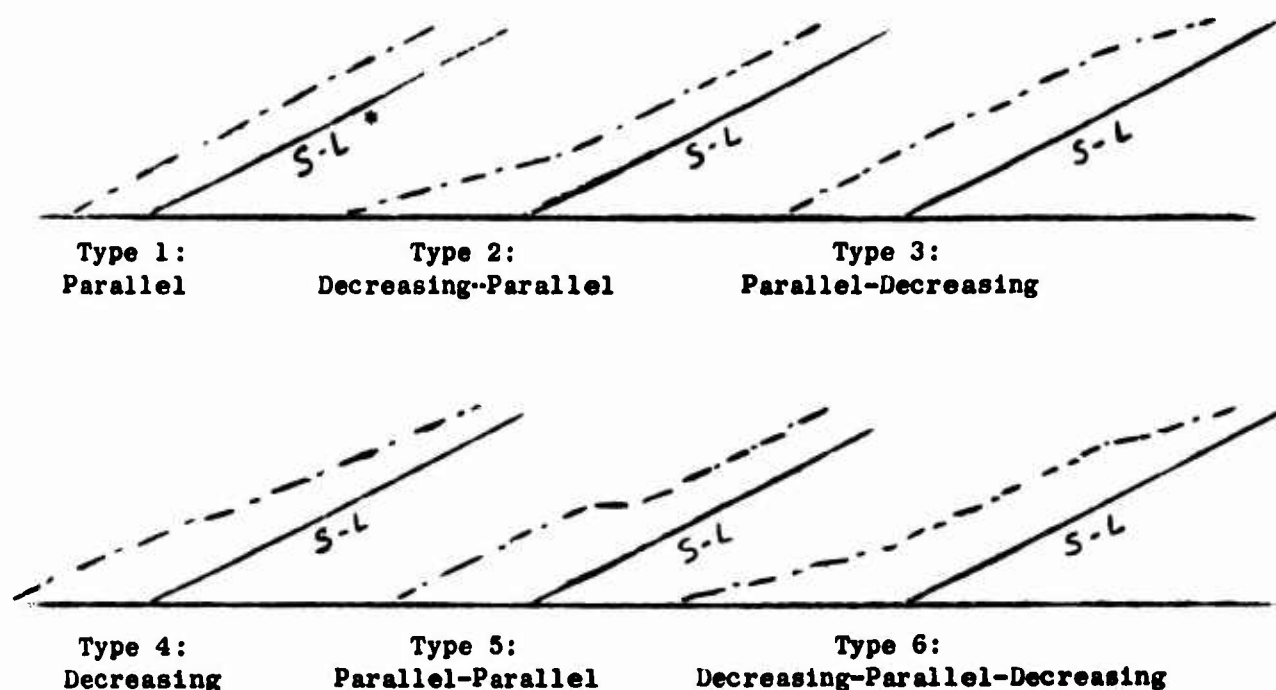
never increases by going upward.)

Type 1:   Type 2:   Type 3:
Parallel   Decreasing-Parallel   Parallel-Decreasing

Type 4:   Type 5:   Type 6:
Decreasing   Parallel-Parallel   Decreasing-Parallel-Decreasing

FIG. 6.   Six dominant types of stationary critical fungus-
          supply level curves plotted within respective
          IC-diagrams

          * S-L means Starvation Line

Other than the stationary curves, another major type is cyclic. Each S belonging to this class chooses fungus for a period of time, then switches to uranium, then after a while returns to fungus, and so on. Then there is a mixed type; the behavior of the Ss in this class is sometimes stationary and sometimes cyclic. And, of course, there are other Ss whose behavior has no obvious regularities. Fig. 7 shows the classification of Group 3 Ss into these four categories for each of the four sessions. The percentages of Ss belonging to the cyclic and the mixed classes do not show much systematic change as the session proceeds. The most dominant session effect takes place in the form

of a steady increase in the "stationary" class and the corresponding decrease in the "neither" (or random) class. So, although it was not apparent in Fig. 5, the learning process seems to be continuing from Session 3 to Session 4. This raises some questions.
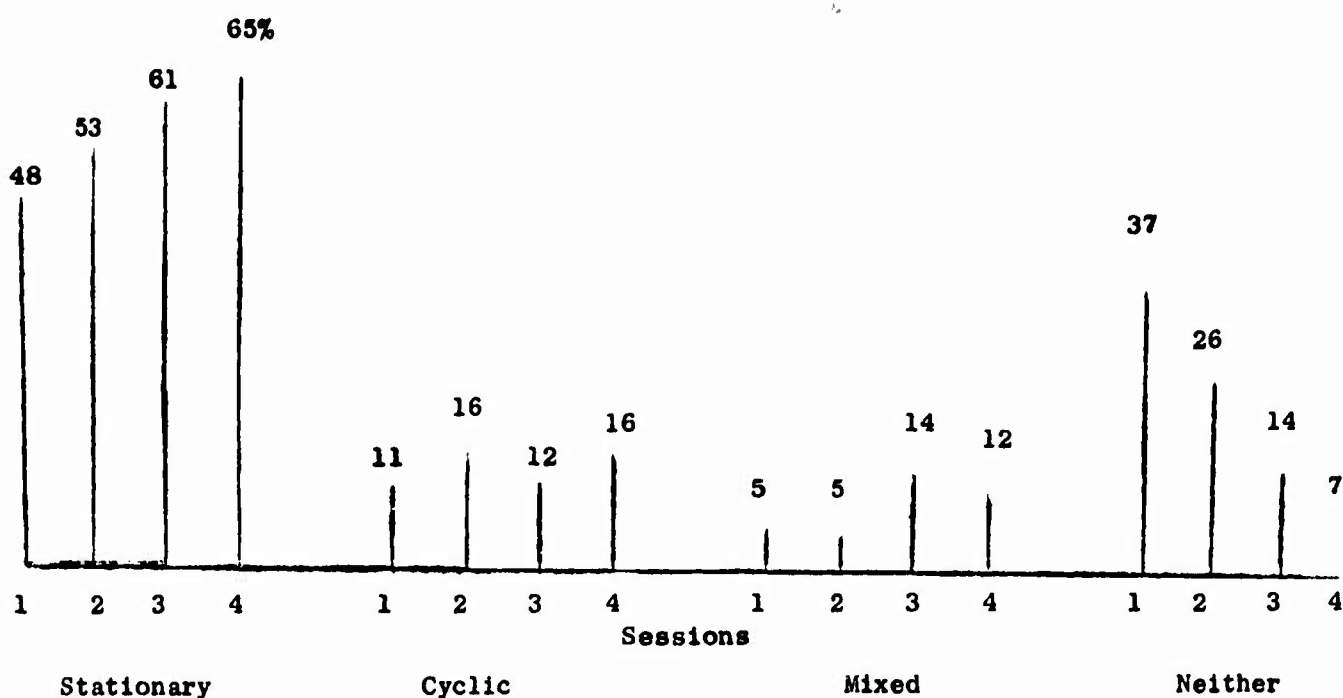
FIG 7. Classification of G3 Ss according to the characteristics of their critical fungus-supply level curves in each of the four sessions (p = 0.35 for Sessions 1 and 2, p = 0.5 for Sessions 3 and 4)

Insofar as the "stationary club" keeps gathering more and more members each session, there should be some real advantage in the stationary strategy, even though setting up a stationary critical fungus-storage level is not the optimal strategy in Case 1. But the experimental situation is not exactly Case 1, either. The experiment must be terminated sooner or later. It is not Case 3 either, since Ss did not know exactly when it would be terminated. So,

to be exact, this is a new case, Case 5, which is characterized by a probability function $\pi(t)$, $0 < \pi(t) < 1$, where $\pi(t)$ is the probability that the experiment will not be terminated by the experimenter at the t-th trial, or the probability that the fungus-eater survives through his t-th age if his stomach is not empty. And we found the solution for this new case. The optimal strategy is, indeed, to establish a critical level of fungus supply. The function is given by a straight line parallel to the starvation line when $\pi(t)$ is a constant. The critical line coincides with the starvation line when $p\pi(1 + \pi + \pi^2 + \ldots + \pi^{a-1}) = \dfrac{p\pi(1-\pi^a)}{1 - \pi} < 1$, in which case the optimal decision is to choose uranium all the time. (We are defining the critical fungus-supply level here as the <u>maximum</u> fungus supply at which the optimal decision is F, instead of defining it as the minimum fungus-supply at which the optimal decision is U.) When it is greater than one, the critical line is separated from the starvation line. We have not yet computed the value of π which locates the optimal critical supply level at around 5 futs.

Probably, a more realistic representation of the experimental situation will be given by a monotone decreasing survival probability $\pi(t)$. In that case the optimal critical fungus-supply curve is a curve monotonically approaching the starvation line. So the Ss were right after all. Some of them immediately used the optimal strategy, and some others learned to use it.

This is very interesting indeed, since we can hardly believe that Ss could solve this difficult dynamic programming type problem (with a discount factor π) using their own brains at the time of the experiment. It is still harder to believe that they could learn the optimal strategy through experience, since the experience cannot have much diagnostic feature when pa is close to one.

So our current hypothesis is that this Case 5 is actually a very familiar situation in our daily life, appearing with various disguises in our experience, and every normal adult has already learned how to cope with this type of situation. So what our Ss should have learned in our experiment was to recognize and identify the given experimental condition as one of the familiar Case 5 situations which they knew how to cope with.

Of course, our experiment cannot provide any decisive evidence concerning whether or not people, or at least college students, can behave optimally in Case 5 situations, because our experiment was not originally designed for the purpose. We should run a new experiment in which the value of π is given explicitly, and then determine the sensitivity of Ss' critical fungus supply level to a change in the value of π. However, we can pick up some more indirect evidences, pro or con, from the present data. For example, the difference between the behaviors of Group 2 and Group 3 in Fig. 5 may acquire a new significance from this new angle. They both started out exhibiting similar curves in Session 1. In Session 2, however, the stationary club in Group 3 had already acquired enough members to create a sharp drop in the fungus-choice ratio curve. The Group 2 data have not yet been analyzed according to the Ss' club memberships. However, the fact that Group 2 curves fail to develop any significant sharp drop effect comparable to the one in Group 3 curves seems to indicate that the stationary club in Group 2 did not succeed in gathering more members as session proceeded, and for a good reason: the stationary club in Group 2 definitely does not represent the optimal strategy no matter what the value of π may be.

There are more, inconclusive but favorable, evidences. We analyzed the

Group 3 data further, and picked up those Ss, separately for Sessions 1 and 2 combined and for Sessions 3 and 4 combined, who are the members of the stationary club and who exhibited a fairly constant critical level, and they are classified according to the value of this critical level. In Fig. 8, the percentages of Ss in this subgroup are plotted against the value of the critical level. Note that the mode of the curve is shifted from 5 to 4 as the probability changes from 0.35 to 0.5. Although one might question the significance of this shift, the direction of the shift is again reasonable, since when the environment becomes richer in fungi, the fungus-eater is entitled to be less concerned about his fungus savings. [5]
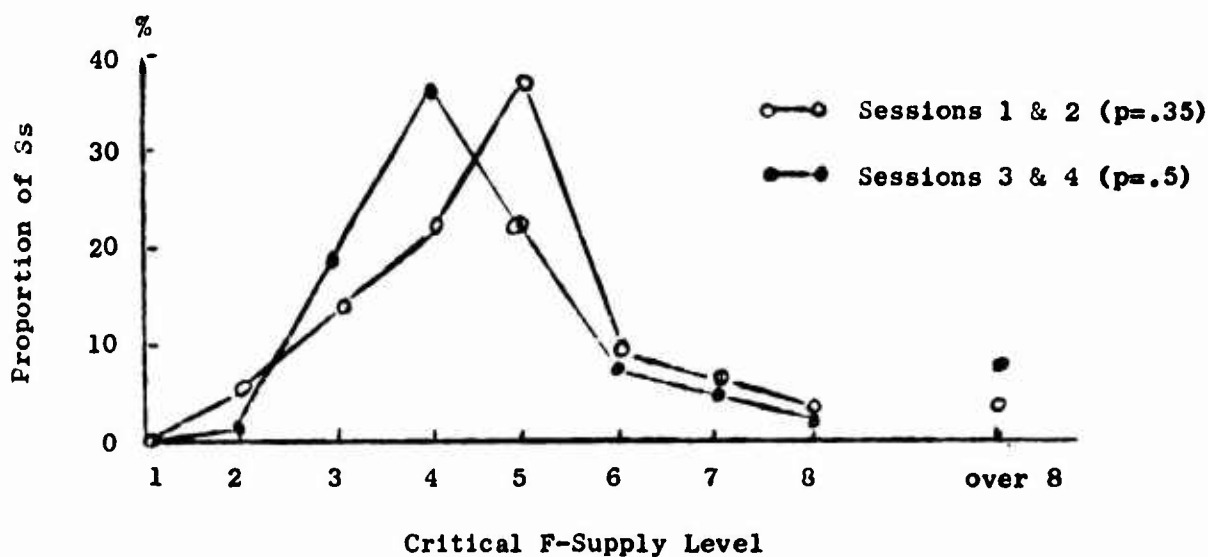

FIG. 8. Classification of selected G3 Ss according to their dominant critical levels

6. Conclusion

This short inductive intermission has helped us in carrying our deductive approach ahead. Although the evidence we obtained in this experiment is inconclusive, it encourages us to pay more attention to this method in order to learn more about human competence in handling complicated dynamic situations. Obviously, the most important factor contributing to the success of this kind of approach is balanced progress in both the deductive and the inductive sides. Without knowing the optimal strategy we will not be able to properly evaluate Ss' behavior, and without inductive feedback we will lose our way in the infinite possibilities of deductive search. Unfortunately, however, we envisage a tough obstacle lying ahead of us in the deductive direction. As will be seen in the solution of Case 5 which will be published soon, our technique of solving these problems analytically is rather clumsy. It seems that we may soon reach an impasse and note that Case 5 is a very simple case indeed compared to the whole array of dynamic situations people deal with in their daily life. A technological breakthrough is badly needed. By asking for analytical solutions we might, however, be asking for too much. As dynamic programming problems are usually solved numerically, we have much less trouble in getting numerical solutions and with numerical solutions we can at least evaluate Ss' behavior. But if we are content with numerical solutions alone, some essential part, though not all, of the original purpose of our approach of creating a deductive branch of behavioral science will be lost.

A fungus, rich in mathematical content, is badly wanted to enable us to proceed further. However, for the time being, let us collect scattered uranium pieces around us by inductive means.

FOOTNOTES

1. Th is paper is a modified version of Toda's colloquium talk given at the Department of Psychology, UCLA, June 1, 1967. The authors are grateful to Drs. Marschak, Brown and MacCrimmon at the Western Management Science Institute, Graduate School of Business Administration, UCLA, for their helpful suggestions, and to Drs. Umeoka, Takenaka, Teraoka, Nakahara and Imai for their suggestions and encouragement. The preparation of this manuscript was supported by contracts or grants from the Ford Foundation, National Science Foundation, and Office of Naval Research.

2. Hokkaido University.

3. Make, for example, the fungus-eater's stomach capacity (fungus-storage capacity) finite. Then the optimal strategy is to try to fill it up all the time.

4. Another interesting aspect of this group of curves is the positive slope of Session 3 curve at its left end. At least some Ss seems to have learned through experience to give up survival when their fungus-storage is running short.

5. For example, consider the extreme case of $p = 1$. Then, obviously, the optimal strategy is to set the critical fungus level at 1 fut, meaning that the fungus-eater should choose F when the storage is just one fut, and choose U when it is two.

REFERENCES

Miyamae, H. "An Experiment on the Fungus-eater Game 4." B. A. dissertation, Department of Psychology, Hokkaido University, 1965.

Nakahara, J. & Toda, M. "Optimal Strategies and Human Behavior in Fungus-eater Game 4." ESD-TDR-64-237, 1964.

Toda, M. "The Design of a Fungus-eater: A Model of Human Behavior in an Unsophisticated Environments." Behavioral Science, 1962, 7, 164-183.

Toda, M. "The Optimal Strategies in Some Simple Fungus-eater Games." Institute for Research Rep. No. 1, 1963.

Toda, M. "Pre- and Postdecisional Processes of the 'Fungus-eater'." Predecisional Processes in Decision Making: Proceedings of a Symposium, AMRL-TOR-64-77, 1964.

Toda, M. "Fungus-eater Games: A Dynamic Approach to the Logic and Psychology of Decision Strategies." Hokkaido Report No. 7, 1964.

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13 ABSTRACT

The purpose of the fungus-eater approach is to obtain the optimal decision rules that handle means-end relations prescribed by a dynamic programming type situation to produce the maximum expected end-value. An experiment recently done at Hokkaido University is analyzed, and the behavior of human subjects is compared with the optimal behavior of the fungus-eater. Under the situations employed in the experiment, the fungus-eater model seems to work well for predicting the human SR behavior.

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